UCRL- 92585
PREPRINT

ELECTRON-BEAM SOURCE DEVELOPMENT FOR MAGNETIC FIELD ALIGNMENT ON MFTF-B

B. W. Rice
J. S. Sullivan

This paper was prepared for submittal to 11th
Symposium on Fusion Engineering
Austin, Texas
November 18-22, 1985

October 2, 1985

Lawrence Livermore National Laboratory

ELECTRON-BEAM SOURCE DEVELOPMENT FOR MAGNETIC FIELD ALIGNMENT ON MFTF-B

B. W. Rice and J. S. Sullivan,
Lawrence Livermore National Laboratory
P. O. Box 5511, L-642
Livermore, CA 94550

Abstract

For proper physics operation of the Mirror Fusion Test Facility (MFTF-B) tandem mirror experiment, alignment of the superconducting magnet coils is critical. A narrow (1 mm diameter), low-energy electron beam is used to trace out the field lines along the axis of the machine. Six crossed-wire detector assemblies are located at various axial positions. The crossed-wire detector is used to locate the electron beam and can trace out flux tubes up to 20 cm in radius.

In this paper, we describe the design and prototype development of a 1 mA, 10 kV e-beam source used for this diagnostic. Dispenser cathodes are used due to their long lifetime operating at rather high current densities. The current range of 0.1 to 1 mA was chosen to provide good signal-to-noise, while the energy range of 1 to 10 kV is necessary to closely follow the field lines and to avoid space-charge spreading of the beam.

Experimental results from a prototype gun operating in a 1 kG field are presented. In particular, we have measured the e-beam profile as a function of magnetic field strength, beam energy, and neutral pressure. In most cases, the beam diameter was found to match closely the limiting aperture on the e-beam source grid. Also, the effect of secondary-electron emission off the detectors is investigated. Data on the poisoning of dispenser cathodes is also presented.

"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48."

Introduction

The Magnetic Field Alignment (MFA) diagnostic consists of an e-beam source located in the center cell and six detectors located in the transition and anchor regions of MFTF-B. A thin pencil beam emitted from a known location will follow the field lines and can then be detected at critical points along the machine axis (see Fig. 1). This information is used to adjust trim coils to minimize geodesic curvature. A complete description of the diagnostic can be found in a related paper by F. Deadrick et al. [1].

The purpose of this paper is to describe the design, construction, and prototype testing of the e-beam source used in the MFA diagnostic. Although the requirements for beam current and energy are not difficult to achieve, the unique environmental conditions prohibited the use of a commercially available system. Instead, the approach taken was to modify a standard e-beam gun used in CRTs to our specifications. Extensive testing was then done to verify that the source satisfied the requirements necessary to achieve the desired magnetic field alignment accuracy.

Source Design Requirements

The basic requirement on the overall MFA diagnostic is the ability to locate field lines to within $\pm$ 1 mm. Thus, the e-beam size, uniformity, energy, and current must be consistent with this goal.

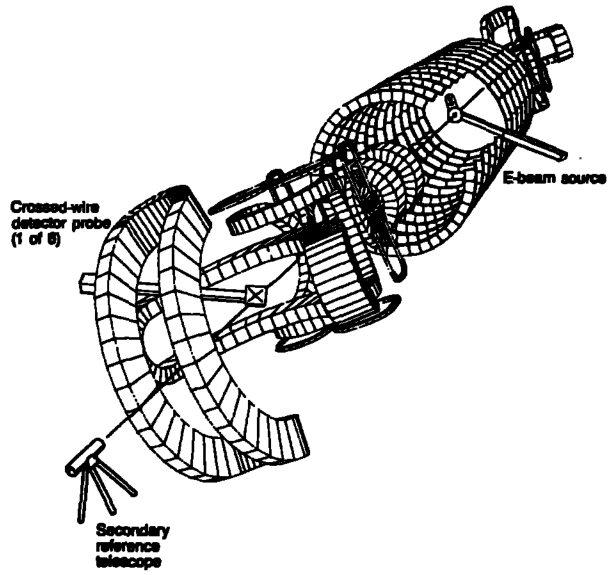

Figure 1. MFTF-B magnet set and the MFA diagnostic.

Ideally, the e-beam diameter should be 0.5-1 mm. Due to the strong magnetic field there is no need for a focused beam, and hence a simple triode structure is adequate where the beam diameter is defined by the smallest aperture (typically the grid). As the beam propagates down the magnet set it transforms into an ellipse where the major axis is up to four times the original beam diameter. Therefore, it is necessary to have a Gaussian-like beam profile with some degree of uniformity and symmetry so that the beam center can be determined in the detector plane. In a strong magnetic field, this distribution is determined by the characteristics of the emitting surface which should be uniform across the grid aperture.

The beam energy range is limited by possible sources of beam distortion or offset such as space-charge spreading and single-particle drifts due to ∇B and field curvature. The drift due to ∇B and field curvature is

$$V_d = m\left(v_\parallel^2 + v_\perp^2/2\right)/qRB \tag{1}$$

where R is the radius of curvature of the field lines. Note that the drift velocity is proportional to the electron energy, giving an upper bound on the beam energy. Calculations show that a beam energy of less than 10 keV will keep the accumulated error to less than 1 mm. The lower bound on beam energy is limited by space-charge spreading of the beam and practical considerations in electrode spacing. To first order, the space-charge accumulation in the beam will produce a radial electric field causing an E x B helical drift of the beam. This in itself should not cause any difficulty, however, second order effects have not been modeled. To be safe, the beam can easily be neutralized by raising the background gas pressure with helium. Calculations show that a backfill pressure of 1.0E-6 Torr will effectively neutralize a beam of energy 1 to 10 keV. So we have chosen an operating range of 1 to 10 keV and a nominal operating energy of 3 keV.

The e-beam current is limited on the high end by thermal considerations. The aluminum wires used for beam detection are somewhat fragile (and inaccessible for repair), so the heat loads must remain low in order to keep the wire from melting. A limit of 10 W was established which gives a maximum beam current of 1 mA at 10 keV. A beam current of 1 mA over an aperture of 0.75 mm gives a current density of 0.23 A/cm^2 which is readily obtainable with conventional cathodes. The lower limit on emission current is basically determined by signal/noise considerations. In a low noise environment, currents on the order of fractions of microamps can easily be detected. Since the noise environment during full operation of MFTF-B is somewhat unknown at this point, a current range of 0.1 to 1 mA has been chosen to provide a reasonable margin of safety.

Due to the limited vessel access and the long time to repair (minimum one month for repairs internal to vessel), the lifetime of the cathode is critical. A minimum lifetime requirement of 500 hours has been established.

A summary of the e-beam source requirements is listed in Table 1.

Table 1. E-Beam Source Requirements

Parameter	Nominal Value	Range
Beam energy	3 keV	1-10 keV
Beam current	0.1 mA	0.01-1 mA
Beam diameter	0.75 mm	0.5-1 mm
Lifetime	>500 hrs	----

In addition to the above requirements, the effect of the MFTF-B environment must also be considered. At the source location in the center cell, the guns will experience large temperature fluctuations, a 10 kG B-field, and a neutron flux. An additional consideration for dispenser or oxide cathodes is the background gas pressure. Of particular concern are the partial pressures of O_2 (or air) and H_2O which will poison the cathode at ~ 1.0E-6 Torr [2]. Table 2 lists the major environmental factors, along with the best and worst case pressures.

Table 2. Characteristics of MFTF-B Environment

Base pressure (nominal)	1.0E-8 Torr
Base pressure (worst case)	5.0E-5 Torr
Partial pressures (worst case)	1.0E-6 Torr of O_2 1.0E-5 Torr of air
Pressure during e-beam operation	≈1.0E-6 Torr of helium
Temperature range	-100 to 100°C
Magnetic field	1 T
Neutron flux	0.1 rads/sec

E-Beam Source Description

A simple triode construction has been adopted for the basic design of the e-beam source as illustrated in Fig. 2. Due to the strength of the magnetic field (10 kG), the electron gyroradius is small $r = 2.38 \sqrt{T_e}(\mathrm{ev})/B(\mathrm{G}) = 0.024$ cm for 10 keV electrons. Thus, even at high energies the beam will remain close to the original flux tube and, as a result, there is no need for focusing elements.

Control of the emission current can be obtained by either space-charge control or temperature control of the cathode. Space-charge control has been chosen to provide better current control and more stable operation which is less dependent on the cathode condition. For space-charge limited triode operation, the emission current is related to the grid voltage by

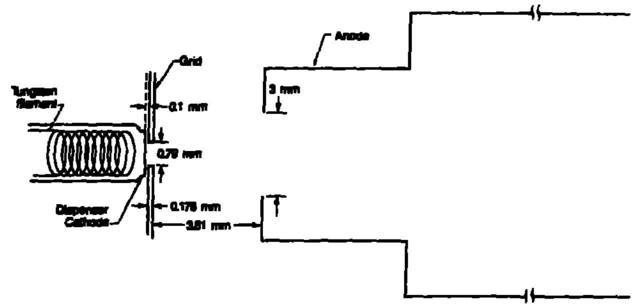

Figure 2. E-beam gun design.

$$I_e = K|V_c - V_g|^{3.5}/V_c^{\,2} \ \mu\mathrm{A} \tag{2}$$

where K is roughly constant ~ 4.5 for guns of this geometry [3]. V_c is the cutoff voltage and is defined as the negative grid voltage required to reduce the emission current to 1.0E-2 μA. The cutoff voltage is given by

$$V_c = V_a/\mu \tag{3}$$

where V_a is the anode voltage and μ is an amplification factor which is a somewhat complicated function of the gun geometry and is best measured experimentally. For the dimensions shown in Fig. 2, the empirically found cutoff voltage is -72 V for the nominal beam energy of 3 keV, and -120 V at 5 kV. According to Eq. (2), with these cutoff voltages the required current range can be satisfied with reasonable grid voltages of -10 to -100 V.

Note in Fig. 2 that the beam diameter is defined by the grid aperture. The anode aperture is made larger than the grid aperture to avoid skimming off part of the beam if the gun is misaligned relative to the field lines.

Several considerations have gone into the choosing of the cathode. In general we considered three basic types: oxide, dispenser, and tungsten cathodes. The tradeoffs between the three types are listed in Table 3.

In view of these tradeoffs, the dispenser cathode was chosen, although tungsten guns have also been acquired as a backup. The dispenser cathode operates at 1100°C and requires a filament current of 0.6 A. The main disadvantage with the dispenser cathode is poisoning. Experience has shown that since the active material is located beneath the cathode surface, the guns can quite easily be reactivated after poisoning at pressures of 1.0E-5 Torr. One other concern is damage to the cathode surface produced by backstreaming ions. These ions would be produced if the neutral pressure is raised to achieve space-charge neutralization. Although this effect has been observed by other experimenters, the problem can be substantially reduced by biasing the anode slightly positive.

The dispenser cathode electron gun was manufactured at Rank Electronic Tubes, Inc., and is shown in Fig. 3.

Table 3. Cathode Tradeoffs

	Advantages	Disadvantages
Dispenser	long lifetime uniform emitting surface lower heater current/temp reactivation after poisoning small JxB force on filament	poisoning O_2, H_2O, air backstreaming ions surface blistering
Oxide	long lifetime uniform emitting surface lower heater current/temp small JxB force on filament	poisoning O_2, H_2O, air difficult to reactivate
Tungsten	no poisoning easy to cycle up-to-air	fragile filaments large filament currents higher heat loads large JxB force on filament nonuniform emitting surface

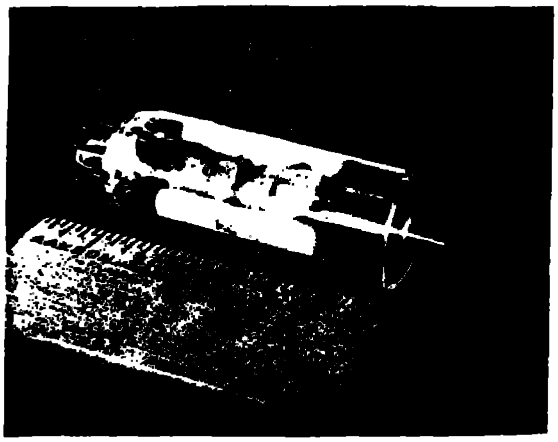

Figure 3. Dispenser cathode electron gun.

System Design

The overall e-beam electrical system design is shown in Fig. 4. Since the source probe is located in the center cell of the vessel, it is necessary to have a gun facing in each direction. An additional gun has been added in each direction for redundancy to achieve the required system reliability.

The e-beam cabling inside the vessel requires high voltage insulation, good vacuum compatibility, temperature operation from -100 to + 100°C, and resistance to neutron radiation. A 20 gauge kapton insulated cable was manufactured to satisfy these requirements. Outside the vessel a heavy gauge RG213 is used to minimize the IR voltage drop through the long cable lengths. Note that the guns are wired in pairs to reduce the number of vacuum cables. The desired gun is selected by energizing its filament.

The power supplies are located in the plasma diagnostics local control area approximately 230 ft from the e-beam sources. They are commercially available power supplies which operate in a depressed cathode mode. This is necessary because the vessel and detectors are at ground potential. The filament supply is dc to avoid any fluctuation of the filament in the magnetic field. If necessary, the anode can be biased positive to reduce backstreaming ions.

Mechanically, the e-beam guns are mounted in the structure illustrated in Fig. 5. Each gun fits into a socket machined out of polyimide. This material was chosen for its good, high-voltage characteristics, wide temperature range of operation, and neutron resistance. The set screws are provided to fine adjust the gun aperture to the required position. The flexible finger stock allows the glass tube surrounding the triode elements to expand and contract

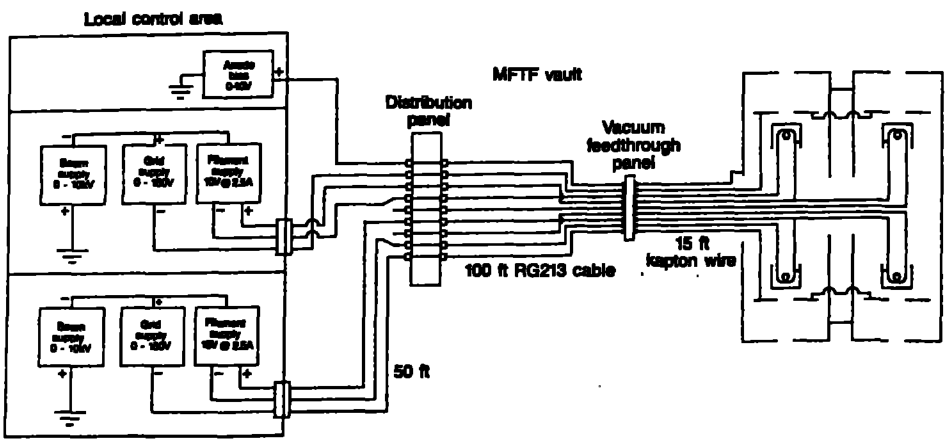

Figure 4. E-beam electrical system.

independent of the surrounding structure. This structure is mounted at the end of a carriage which moves linearly in a plane perpendicular to the vessel axis. The source head itself can be rotated about the vessel axis. The linear and rotation motion combined allow the e-beam source to trace out a flux tube up to 20 cm in radius.

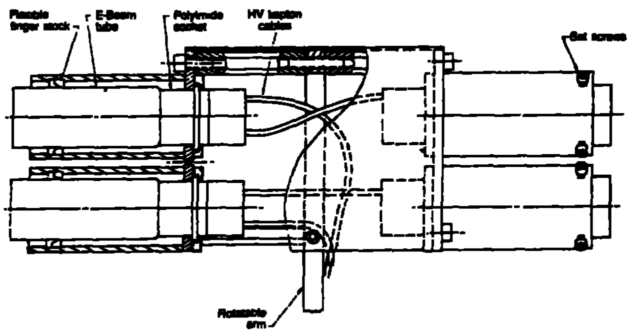

Figure 5. Mechanical support structure.

Prototype Results

A schematic of the apparatus used to test the prototype e-beam guns is shown in Fig. 6. The maximum magnetic field is about 1 kG and is fairly uniform along the axis. The gyroradius at 1 kG is smaller than the beam diameter, so no significant change in performance is expected when operating in the actual 10 kG field in MFTF-B. The base pressure of the system is 7.0E-7 Torr. The system is equipped with an RGA head for use in poisoning experiments. A 1.5 mm diameter aluminum wire, of the same type planned for use in MFTF-B, is used to detect and scan across the beam. The collector plate is simply a 2" diameter copper plate used as a beam dump. It was later removed for reasons discussed below.

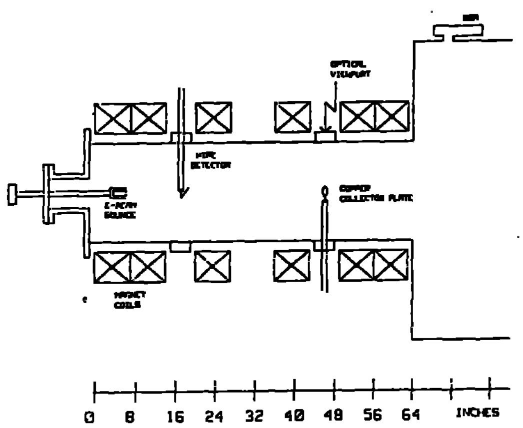

Figure 6. Configuration for e-beam prototype tests.

The major goals of the prototype tests were to: 1) measure e-beam current, energy and spot size in a strong magnetic field; 2) determine the effect of poisoning on the dispenser cathode; 3) quantify the effects of secondary emission off the detector; and 4) test a tungsten cathode e-beam source as a backup.

The dispenser-cathode sources which are tested here have the dimensions given in Fig. 2. In general, the guns operated well in the magnetic field, with the emission current essentially following Eq. (1) above. Equation (1) is plotted in Fig. 7 for energies of 3 and 5 kV. The I/V curves for ten guns were measured and most fall within the error bars in Fig. 7. The guns were operated successfully from 1 to 8 kV where the 8 kV limit is due to surface breakdown across the glass base of the gun. The high voltage operation could have been extended by repackaging of the electrodes, but it was not viewed as necessary for operation of the diagnostic.

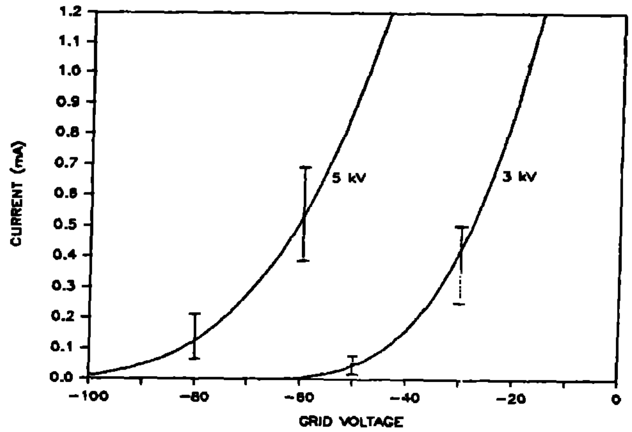

Figure 7. Emission current vs grid voltage.

Two difficulties, each somewhat unique to this application, were encountered in obtaining the expected emission current and deserve mention here.

The first is that care must be exercised when conditioning the cathodes. Unlike typical electron tubes which remain under vacuum continuously, the e-beam sources in this application will frequently be cycled up to air. The dispenser cathodes are hygroscopic and, as a result, tend to expand and blister if heated too rapidly after an up-to-air cycle. This can result in a short between the cathode and the grid. Thus, care has been taken to maintain the proper spacing between the cathode and grid during construction of the gun. During conditioning, the cathode is heated slowly over a period of about 15 minutes.

A second difficulty which is encountered when operating the gun in a magnetic field is secondary emission off of the copper collecting plate shown in Fig. 6. Measurements indicate that approximately a third of the beam current incident on the plate is re-emitted as secondary electrons and reflected primary electrons. Due to the axial magnetic field, these electrons are trapped on roughly the same flux tube as the incident beam. As a result, these secondary and reflected primary electrons return to the source and are collected by the anode. This tends to cause unstable emission current from the source and, at high energies, > 5 keV resulted in arcs every few minutes. Larger beam diameters were also observed due to the additional space charge buildup caused by the secondary emission. When the collection plate was removed and the beam was allowed to spread out into the end of the vessel, this behavior did not exist and the anode current dropped to zero as expected.

Previous work on secondary electrons [4,5] indicates that typically 90 percent of the secondary electrons have low energy of less than 20 eV. Thus, it was first thought that the majority of the secondary electrons could be collected by biasing the collector plate at 30 volts. A plot of the secondary emission current vs collector plate bias is shown in Fig. 8. Note that the secondary emission drops by only 40 percent with a 30-volt bias. The secondary current was observed to be approximately constant with bias levels up to a few kV, indicating that the majority of the re-emitted current is actually reflected primaries. Although the percentage of reflected primaries seems unusually high, it has been noted [4,5] that this percentage is a sensitive function of the collector temperature, which in these experiments was observed to glow red hot at the point of beam incidence.

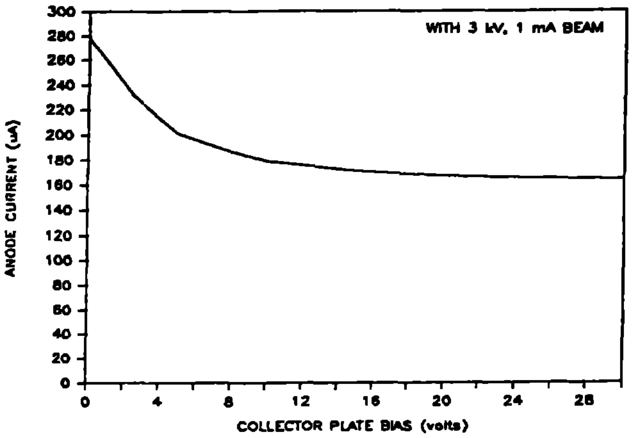

Figure 8. Secondary emission vs collector bias.

The detector wire causes similar feedback problems if left in the beam for more than 30 seconds (again indicating that the detector temperature affects the secondary emission energy spectrum). Indeed, if the detector wire is left in the beam for more than 30 seconds, it begins to melt and deform. Thus, to avoid problems with reflected primaries and melting the detector wire in MFTF-B, the control electronics for the detector probe have been designed to scan the beam in less than a second and have protect switches such that the detector wire cannot stop in the beam path. Also, there is no collector plate planned for use in MFTF-B. Instead, the beam is left to expand into the end fan and is collected by the end dome of the vessel. In this case no electron feedback to the source is observed.

With the collector plate removed, stable source operation is observed with a smooth beam profile as shown in Fig. 9. The detector wire is larger than the beam, so the width observed in this plot is more an indication of the wire diameter than the beam width. Note, however, that the beam center can easily be determined to within a fraction of a millimeter, thus satisfying our requirements. Similar beam profiles were taken at several different values of emission current and beam energy with very little change.

Beam profiles were also taken with different levels of helium backfill pressure which is used for space-charge neutralization. The neutral pressure had little effect on the beam profile, probably because the distance between gun and detector is only 30 cm. In MFTF-B, where the separation between source and detector is as large as 20 m, the effects of space-charge spreading will probably be more severe and will require the helium backfill. One additional benefit of a helium backfill is that at 3 keV and 1 mA the beam becomes visible at pressures of about 1.0E-4 Torr and could possibly be used for the initial rough alignment. Due to the large diameter of the MFTF-B vessel, however, the beam will probably be too dim to use for this purpose.

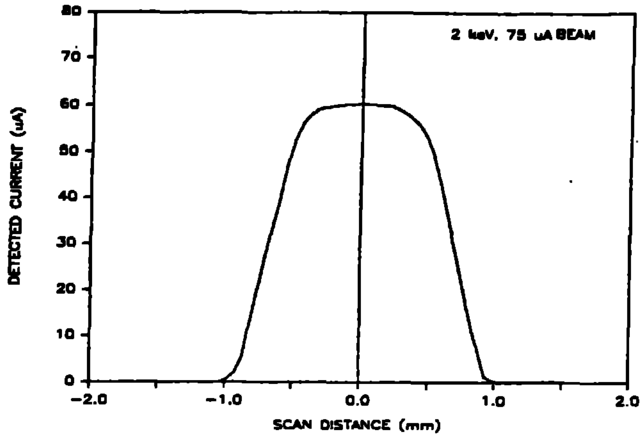

Figure 9. E-beam profile in a 1 kG field.

The effect of magnetic field on the beam profile is shown in Fig. 10, where the beam is scanned at 850 G and 85 G. At 85 G the gyroradius becomes quite large ~ 0.5 cm and, as can be seen in Fig. 10, the profile spreads out accordingly. No change in beam profile is expected in going from 1 kG to the 10 kG field in MFTF-B because the beam is determined by the grid aperture at both field values.

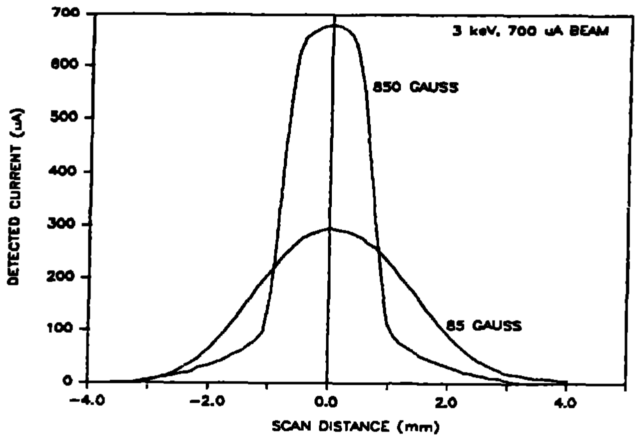

Figure 10. E-beam profiles vs magnetic field strength.

Poisoning tests were run on the dispenser cathodes to determine the sensitivity to water or air leaks within the vessel. Typically, the base vacuum in MFTF-B is 1.0E-8 Torr, so only in a fault mode would we expect the guns to be poisoned. At neutral pressures of 1.0E-5 Torr (air), the emission current was reduced by a factor of 10. RGA scans indicated that this corresponded to a partial pressure of about 1.0E-6 Torr for both O_2 and H_2O, which are the main causes of poisoning. In the above tests, the gun was able to fully recover after the leak was terminated. At air pressures of 1.0E-4 Torr, the emission current was essentially reduced to zero, but the gun was able to reach 65 percent of its original emission current upon reactivation. This data gives confidence that the guns are fairly resistant to poisoning.

As a backup, a tungsten cathode e-beam gun was tested. In these guns the cathode consists of a thin round tungsten wire drawn across the grid aperture. The filament current is 3 amperes. Although the guns operated consistently and reliably in the magnetic field, the beam profile proved to be asymmetric as shown in Fig. 11. The asymmetry is due to the fact that the tungsten wire fills only a portion of the grid aperture. In addition, the wire filament is probably deflected somewhat due to the J x B force.

The beam profile for the tungsten gun could probably be improved by using a ribbon type filament.

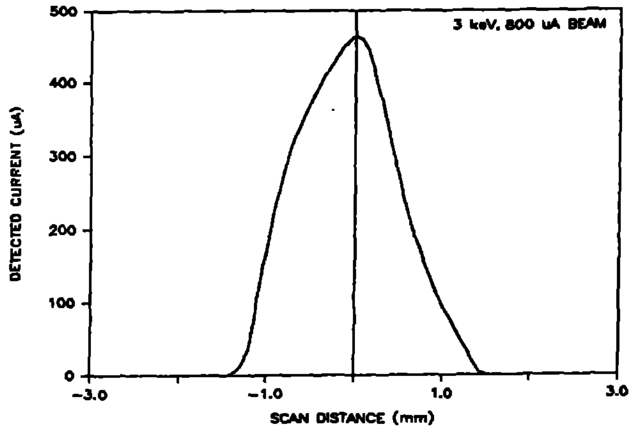

Figure 11. E-beam profile, tungsten cathode.

Conclusion

An e-beam source has been designed and constructed for use with the magnetic field alignment diagnostic on MFTF-B. The source is based on a simple triode design using a dispenser cathode. Extensive testing has demonstrated that the guns satisfy the unique physics and environmental requirements. The sources are currently installed in MFTF-B, and magnetic field testing is under way.

Acknowledgments

We would like to thank the people at Rank Electronic Tubes, Inc., for their assistance in the design and construction of the e-beam guns.

References

[1] F. J. Deadrick et al., "Design of a Magnetic Field Alignment Diagnostic for the MFTF-B Magnet System," Proc. 11th Symp. on Eng. Prob. of Fusion Research, IEEE Publ., 1985.

[2] J. L. Cronin, "Practical Aspects of Modern Dispenser Cathode," Microwave Journal, September 1979.

[3] H. Moss, Narrow Angle Electron Guns and Cathode Ray Tubes, Academic Press, 1968, Ch. 2.

[4] W. H. Kohl, Handbook of Materials and Technique for Vacuum Devices, Reinhold Publishing Corp., 1967, Ch. 19.

[5] K. R. Spangenberg, Vacuum Tubes, McGraw Hill Book Co., 1948, Ch. 4.